

This paper shall discuss the evaluation of the original Dryden X-31 aerodynamic math model, processes involved in the justification and creation of the modified data base and comparison time history results of the model response with flight test.

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**Validation of the NASA Dryden X-31  
Simulation and Evaluation of Mechanization Techniques**

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The aerodynamic capabilities of newer tactical aircraft, such as the X-31, have made modeling of the low-speed end of the envelope increasingly important, particularly at very high angles of attack. The X-31 plans to exploit this region during evaluations of tactical utility of the experimental aircraft with demonstrations of high angle-of-attack, post-stall, 180 degree turns, known as the Herbst maneuver.

On the basis of observations made by Bihle Applied Research, Inc. it was felt that certain changes to the Dryden X-31 simulation data base and data implementation techniques would improve the modeling of the in-control and departure characteristics of the flight test vehicle.

### **Program Background**

- **Original X-31 Simulation Data Base Did Not Adequately Model the In-control and Departure Characteristics of the Flight Test Vehicle**
  - **The Ability to Confidently Evaluate the High Angle-of-Attack Flight Regime in the Sim Environment was Compromised Because of this Uncertainty**
- **Observed That Proper Implementation of Rotary-Balance Dynamic Data Effects May Improve Modeling**
- **Proposed Simulation Evaluation of Implementation of Static, Forced-Oscillation and Steady Rotational Terms On Model Response**



The present task involved checking the current X-31 data base, state variables and mechanization of the moment components. Particular emphasis was directed toward the lateral and directional properties below Mach=0.8. Data used in the Dryden simulation model were plotted against available wind tunnel data for comparison. The Differences were rationalized to reflect the aircraft configuration changes and updates. Further, the simulation was modified to incorporate known asymmetries and expanded for other functionalities to produce a model that was more representative of the test vehicle. Evaluations were made using the original data base, the revised data base, and with Kalviste's method of incorporating rotary-balance and forced-oscillation data in a six degree-of-freedom aircraft simulation against flight test results. Finally, the revised portions of the simulation data base were translated into a compatible format and delivered to NASA Dryden for use in their simulation model.

### **Task Description**

- **Acquire and Examine Current Data Base, Mechanization of Simulation Model, Flight Test Signals**
- **Comparison Plot Data Against Available Wind Tunnel Test Data Base, Rationalize Differences, Revisions**
- **Incorporate Known Asymmetries, Additional Functionalities into Data Base**
- **Evaluate Original / Revised Data Base, Kalviste Mechanization of Rotational Terms to Flight Test Results**
- **Re-format Revised Data Base into DRF X-31 Simulation Compatibility**
- **Document Data Revisions and Simulation Results**

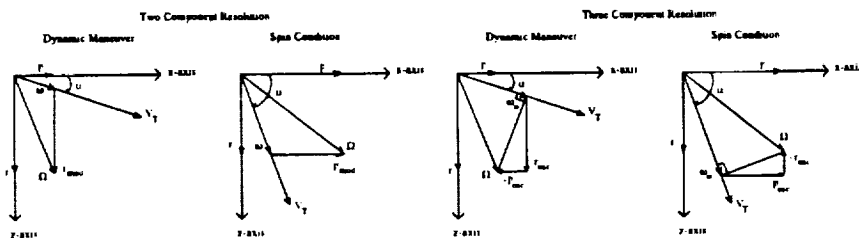


The mechanization of rotary-balance data into the simulation has been the subject of much evaluation in the past few years. An early method that was developed to permit the simulation of spins required the filtering of the wind axis roll rate. This method was successfully used on several early spin simulations, but because of the relatively long time constant involved, it had limited (and occasionally adverse) effects on high AOA rolling maneuvers. The most traditional method of implementing rotary data resulted when the filter time constant was reduced to zero, i.e., the rotation vector was resolved directly on to the velocity vector. This methodology is currently in use in a number of simulations, however concerns about the implications of this method raised by Juri Kalviste when an oscillatory residual opposes the total body-axis rate component (see the vector diagrams in the figure) led to the development of a third method of implementation.

A method was devised that distributes the aerodynamic damping effects based on the relationship of the airplane motion to the actual wind tunnel test motions used to derive the various damping terms. By resolving the airplane rotation into a single body-axis component and a wind-axis component, depending on the relationship of the rotation vector and the velocity vector, the residual body-axis term is always a subset of the total body-axis rate.

### Kalviste Technique

- Direct resolution of wind-axis rotation rate effects from body rates
- Resolves rotation vector into two components, depending on relative position of rotation vector and velocity vector
- Uses dynamic derivatives as obtained by perturbing P and R independently - Rotational data used only if P and R are perturbed at the same time



It has been well documented that forebodies can produce yawing moments in symmetric flight due to asymmetric shedding of the forebody vortices. It has also been demonstrated that the high angle-of-attack aerodynamic characteristics are very configuration dependent and that forebody geometry can have a significant influence on these characteristics.

The X-31 forebody contributes significantly to the propelling yawing moment characteristics of the total airplane at high angles of attack and exhibits static yawing moment offsets. Flight test data also indicates the occurrence of static yawing moments at high angles of attack at zero sideslip. The Dryden X-31 simulation model did not contain the yawing moment asymmetries in the 40 to 80 AOA region that were observed during X-31 wind-tunnel testing and the curve values in the simulation for the basic static directional stability were symmetric.

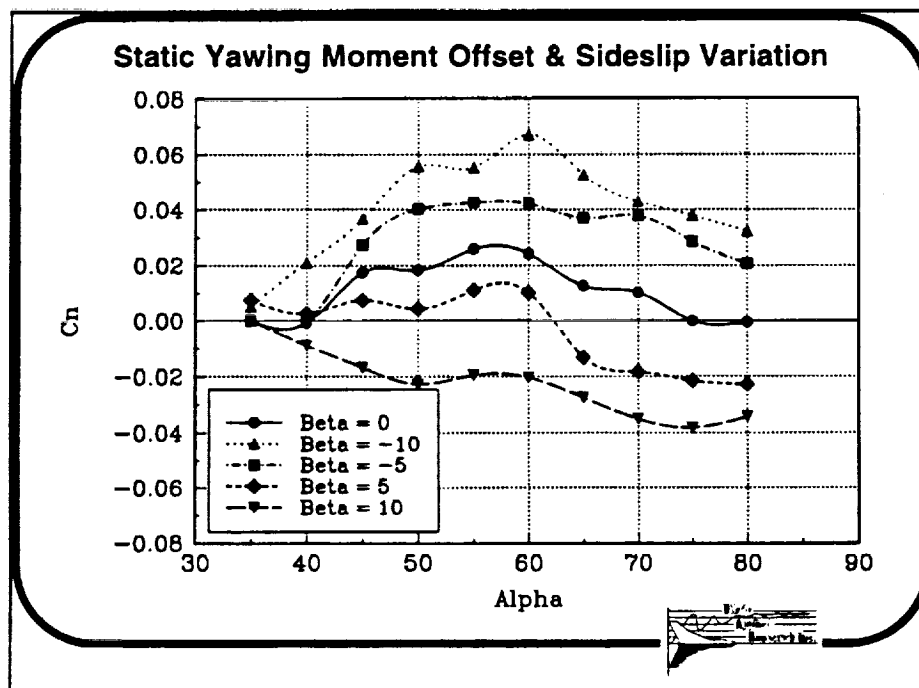
Static data from the NASA Langley 30x60 wind tunnel were obtained to investigate the effect of the yawing moment offset by incorporating the yaw asymmetry at high angles of attack into the simulation model.

### **Incorporation Of Yaw Asymmetry At High AOA**

- **Flight Test Data Indicates Occurance of Static Yawing Moment at High AOA at Zero Sideslip**
  - **Offsets Ignored in Sim Model**
  - **Sideslip Asymmetry Due to Offset Influence Also Needed**
- **Obtained NASA Langley 30x60 Static Data to Investigate Yawing Moment Offset Effect**
  - **Generated Replacement Sim Table for Basic Yawing Moment Incorporating High AOA Offsets on Zero and Non-zero Sideslip**



The static yawing moment versus angle of attack from the wind tunnel tests is presented in this figure. As shown, the zero sideslip offset reaches a maximum value of approximately 0.026 at 55 deg AOA and a non-zero sideslip asymmetry due to the influence of the zero sideslip offset value also occurs for sideslip angles up to 10 deg. A replacement simulation table for the basic yawing moment was generated, incorporating these high angle of attack offsets on zero and non-zero sideslip angles for the tested angle of attack region between 40 and 80 deg. The incorporation of these offsets results in an extended sideslip argument, because of the non-symmetrical nature of the data.



Another concern about the current configuration's rotational yawing moment characteristics was over the presence of the aft fuselage strakes, located along the side of the fuselage, essentially where the unfaired actuators for the thrust paddles were on an earlier tested X-31 configuration. The effect of these aft strakes on the rotational characteristics of the aircraft has never been assessed, but some indication can be gained by examining the actuator effect, found by comparing the earlier (unfaired actuators) configuration with the later (faired actuators) configuration, which indicates a degradation in yaw damping due to the presence of these actuators. Limited free-spin tests also indicated a degradation in the model's characteristics, with the wing rock motions becoming more divergent and the model exhibiting the high-incidence kinematic roll (HICR) departure more readily.

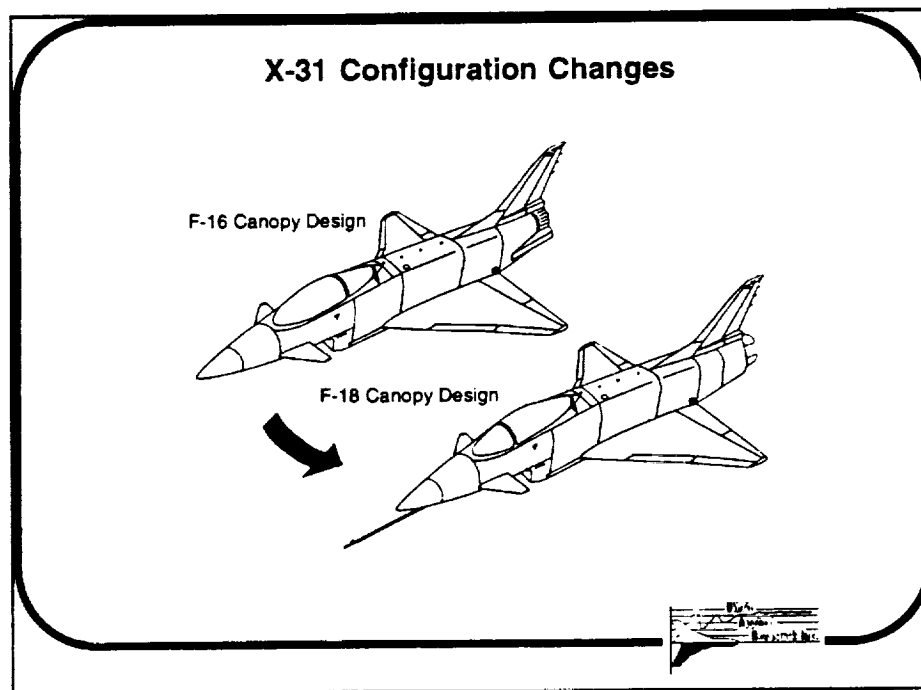
### **Incorporation Of Aft Strake Rotational Yawing Moment Effect**

#### **Aft Strake Considerations**

- **Current Configuration Possesses Aft Strakes**
- **Limited Assessment Of High AOA Dynamic Effects**
  - **No Rotary-Balance Tests with Aft Strakes**
  - **Free-spin Testing Indicated Degradation**
- **Comparison to Earlier Configuration Indicates Degradation with Actuator Surfaces Below Vertical Tail**
  - **Past Experience Has Shown Flow Separation Effects Generated Below Vertical Tail Can Induce Adverse Pressure Field When Rotating**
- **Generated 'Quick-Look' Incremental Rotational Yawing Moment Tables for Limited Study of Aft Strake Effect**

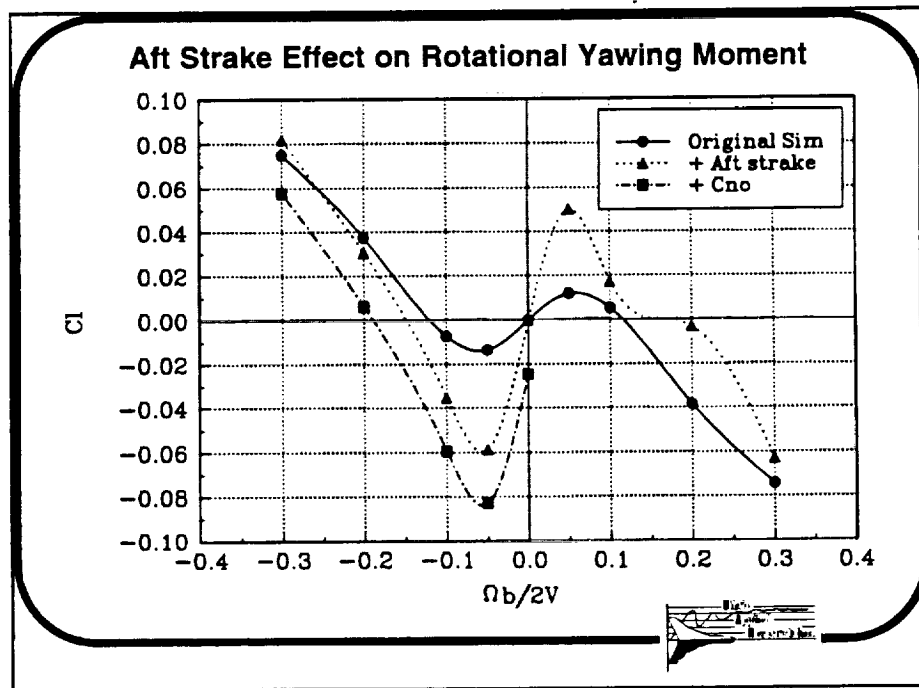


A 'quick-look' set of incremental rotational yawing moment tables were generated for a limited study of the aft strake effect in the departure region utilizing the earlier X-31 configuration yaw damping characteristics with the actuator fairings installed. The earlier configuration exhibits propelling yawing moments out to further rotation rates at 50 AOA and is significantly more propelling in yaw about the velocity vector in the 60 degree AOA region. (It should be noted that for this quick-look the rotational data only covered 40 to 80 AOA, and therefore comparisons below 40 AOA in this case are invalid). Past experience with other military configurations has shown that flow separation effects generated below the vertical tail can induce an adverse pressure field on the vertical tail when rotating in this AOA region. This pressure field can result in lower surface pressures on the windward vertical tail surface at low rotation rates, thus producing propelling yawing moments.





Incorporation of the aft strake effect on rotational yawing moment characteristics for the Dryden X-31 simulation model is shown in this figure. LE Flap=40/32, Canard=-40, Sideslip=0 deg, AOA=60 deg. The first two curves represent only the rotational increment for the original model and for the aft strake effect. The last curve represents the addition of the rotational increment to the static offset curve.



The Bihrl Applied Research X-31 simulation contains a built-in validation routine that allows it to be overdriven with flight test data. The advantage of this ability is to duplicate the conditions and pilot inputs of the flight test maneuver exactly, thereby allowing one-to-one comparisons of the resulting time histories in order to determine model fidelity. In addition, it is not necessary to incorporate the aircraft control system for this procedure.

Flight test obtained states and control deflections were used as inputs to drive the closed-loop simulation to compute the data base generated forces and moments. The output values, in the form of moment coefficients, were analyzed by comparison with the flight-test extracted coefficients. In order to isolate the flight-test aerodynamic moment, the contribution due to thrust vectoring had to be removed. Due to time limitations and the complexity of the engine thrust model in the Dryden simulation, the yawing moment generated by thrust vectoring was approximated by an algorithm developed by Bihrl Applied Research. This simplified algorithm was found to be reasonably accurate for small to intermediate vane deflections, and tended to over estimate yaw due to thrust as the vanes approached the limits of their deflection. Regardless, this estimation scheme permitted a rapid assessment of the available flight data for the limited scope of this study. The yawing moment produced by thrust vectoring was then subtracted from the flight-test extracted total moment coefficient to yield the aerodynamic portion of the generated yawing moment which was used to compare with the data base produced results.

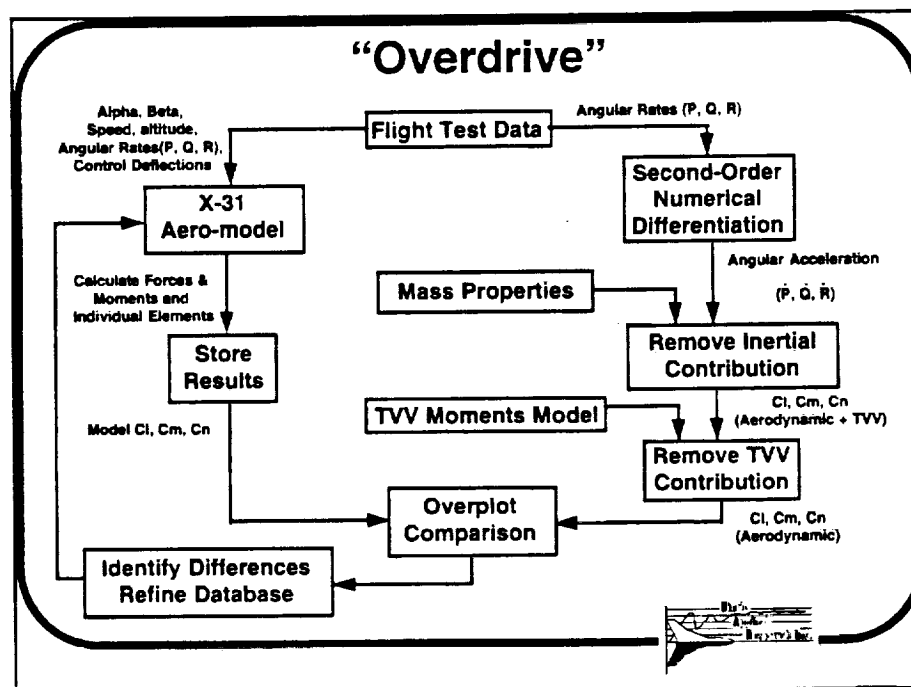
### **Comparison Of Model Response With Flight Test Results**

- **Closed Loop Evaluation Using Selected Flight Test Data**
  - **Simulation Driven by Flight Test Rates and State Variables**
  - **Algorithm Developed to Estimate Thrust Effects**
  - **Routine to Plot and Save Aero Coefficients for Comparison to Flight Test Data**
- **Comparison of Flight Test Results and Driven Sim Response**
  - **Ability to Select Specific Components of Total Coefficients**
  - **Assess Contributions of Effects on Resulting Total Moment**



The BAR closed-loop simulation also stores the time history of each element of the aerodynamic forces and moments. Comparison plots of these components before and after modifications to the data base help to assess the contributions of these effects on the total resulting moment, identify poorly modeled effects, and validate changes to the simulation model. In addition, the BAR simulation also provided options to activate/incorporate rotational data, static yawing-moment offsets, strake effects, and the Kalviste technique for mechanization of the rotary-balance and dynamic derivative data. A utility program was used to produce overplots of flight-test results versus simulation response with the various changes to the model data and mechanization.

A flow chart describing the procedure used for the comparison of X-31 flight test results and the simulation model response is shown.



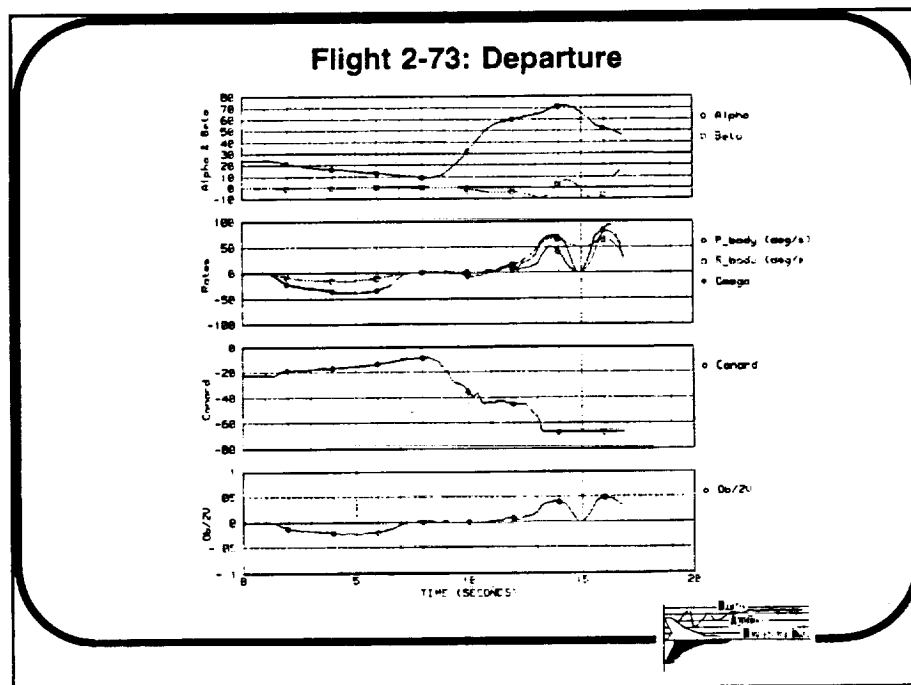
Listed in Table I are the flights investigated in this effort and the corresponding maneuvers performed.

### Flights Investigated

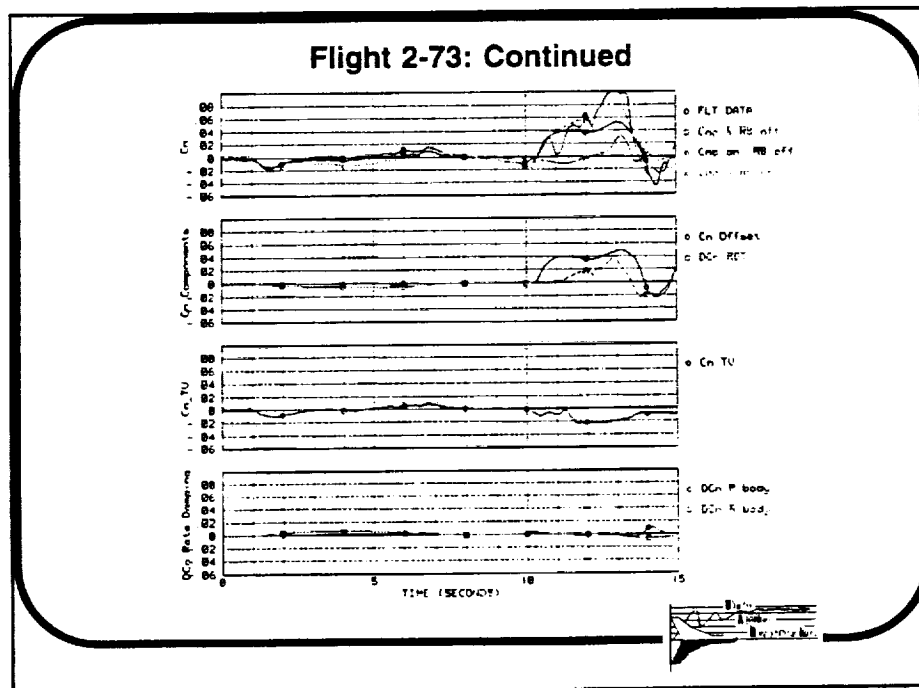
<u>FLIGHT NUMBER</u>	<u>DESCRIPTION</u>
2-73	Departure
2-85	Velocity-vector Roll @ 40 AOA
2-56 (205)	Level Deceleration to 70 AOA
2-56 (360)	360 Left Roll @ 40 AOA
2-56 (361)	360 Right Roll @ 40 AOA
1-116 (.10)	Right Turn + Left Roll + Left Turn @ 10 AOA with Thrust Vectoring
1-116 (.11)	Right Turn + Left Roll + Left Turn @ 10 AOA w/o Thrust Vectoring
1-83 (1083)	Level Deceleration to 50 AOA
1-83 (830)	Full-stick Bank-to-bank @ 50 AOA
1-83 (831)	Full-stick Bank-to-bank @ 55 AOA
1-83 (832)	Full-stick Bank-to-bank @ 60 AOA
1-86	Level Deceleration to 70 AOA, Bank-to-bank



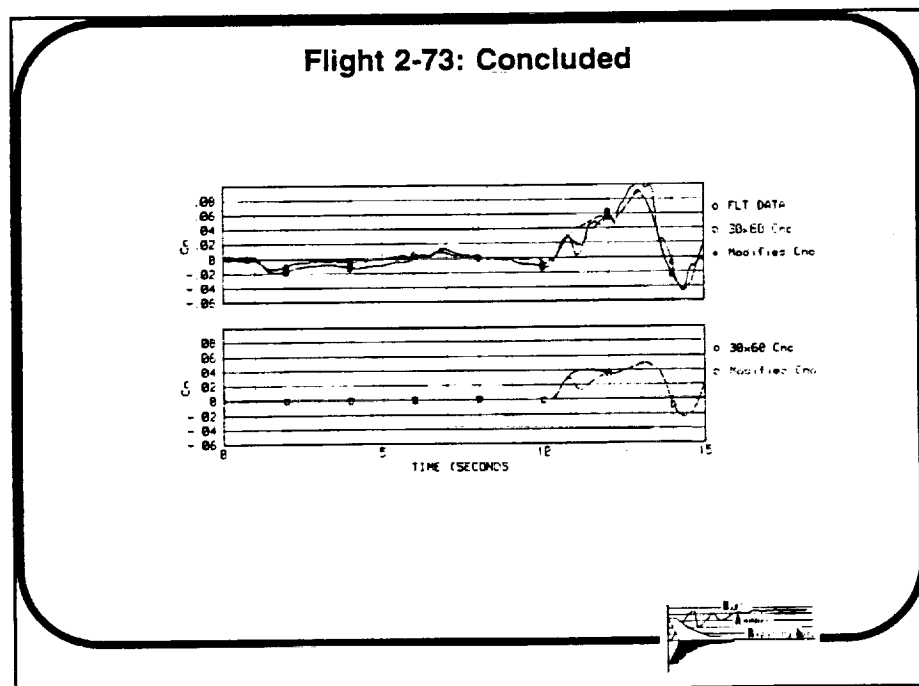
The time history traces for the departure of Flight 2-73 are presented in the accompanying figures. This first figure presents the angle of attack, angle of sideslip, body-axis rates, canard deflection and the non-dimensionalized rotation rate ( $\Omega b/2V$ ) throughout the flight. This flight was flown with Ship 2, Version 1.16 FCS software, with the aft fuselage strakes installed and 'grit strips' on the noseboom and radome. The maneuver was performed at 35,000 ft/0.4 Mach and consisted of a full aft pitch input from inverted flight with maximum afterburner set and the angle of attack limiter set at 60 deg AOA (a split S maneuver). As the aircraft approaches 60 deg AOA, a positive yaw rate and negative sideslip excursion develops. The airplane continues to depart from controlled flight with increasing angle of attack and yaw rate. The angle of attack reached a value of 70 deg, where, the aircraft becomes highly damped in yaw again, preventing the aircraft from obtaining further increases in angle of attack, resulting in a fast, flat spin. The pilot initiated recovery with forward stick and with the angle of attack reduction, the yaw rate damped to zero, completing recovery of the aircraft to controlled flight.



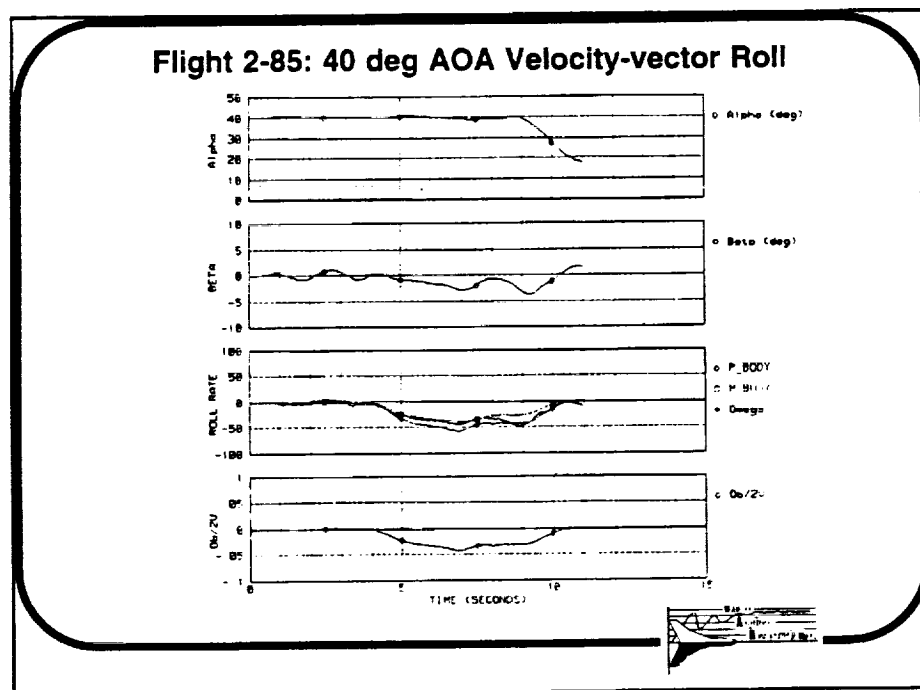
This figure presents the yawing moment propagation for the departure of Flight 2-73, comparing the results of the original simulation model and the modified model response to the flight extracted yawing moment. Also included are the contributions to the total yawing moment of the static offset, rotational effects, thrust vectoring and forced oscillation damping terms (developed when the rotational effects are turned off). The modified model uses Langley 30x60 wind tunnel yawing moment data versus sideslip, including the static offsets, as well as the rotational yawing moment data versus  $\Omega b/2V$ , updated for the aft strake configuration. As shown in this figure, a result that is close to the airplane response only occurs when including both the offset effects as well as the rotary balance terms with the Kalviste method.



Based on flight extraction performed by Dryden, as well as by BAR, a reduction in the static yawing moment offset value was found to occur near 55 deg AOA. By modifying the offset value to reflect this effect, and maintaining the original sideslip variation, the resulting yawing moment time history exhibits an even closer match to the flight extracted yawing moment.



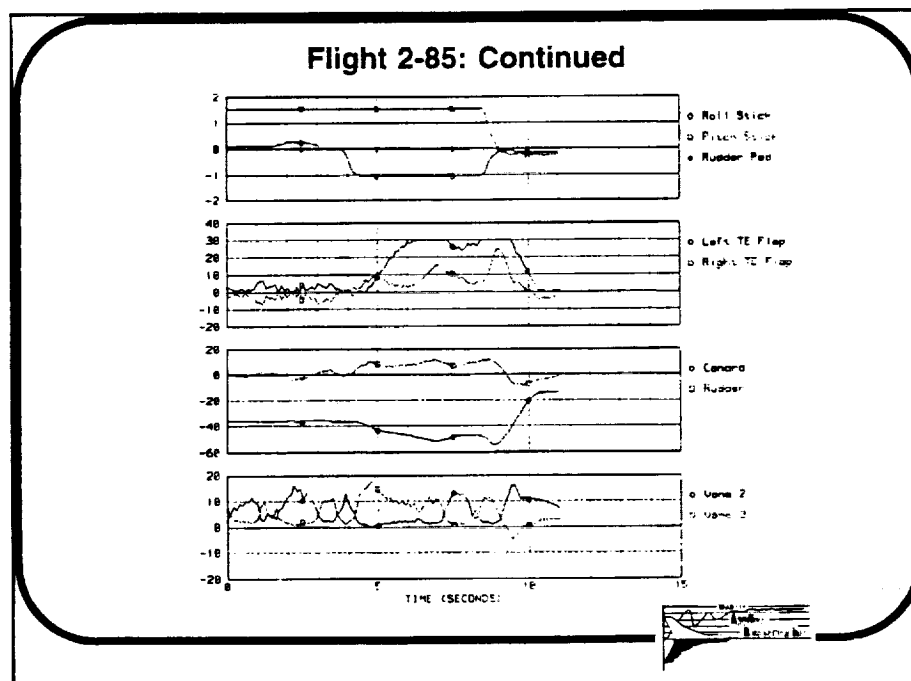
Further evidence of the importance of modeling the rotary terms, particularly in the post-stall region, is shown in the following accompanying figures for Flight 2-85, a 40 deg AOA, 360 deg roll about the velocity vector.



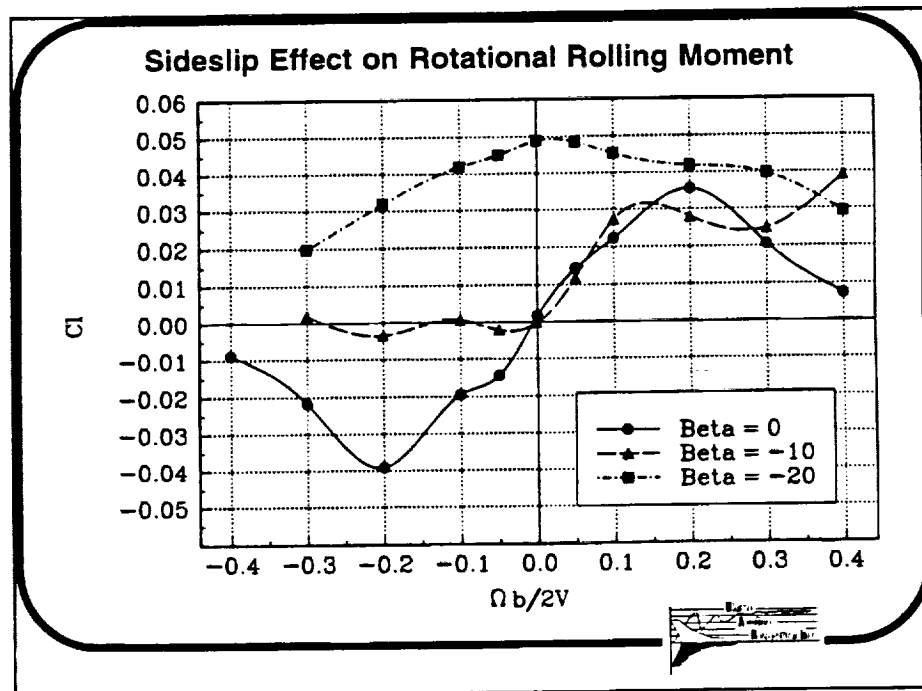


This figure shows the control inputs and deflections of Flt 2-85. It should be noted that the flaperons, following a brief deflection in the direction of the left roll, immediately deflect to near the limit opposing the roll, evidence of a significantly propelling condition at this angle of attack.

When the roll characteristics for this configuration are examined about the velocity vector, this is indeed seen to be the case.

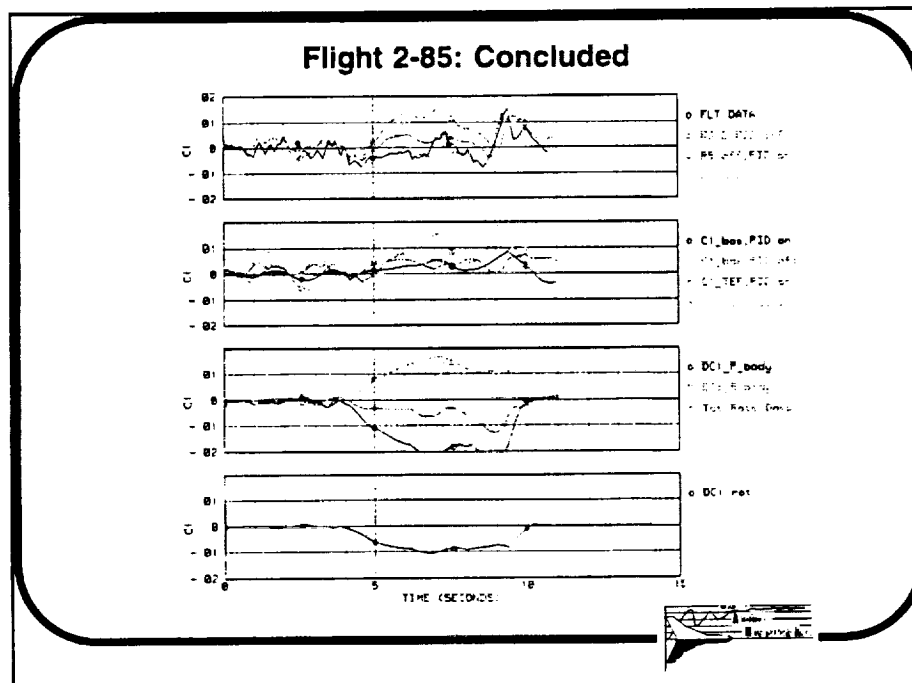


The steady-state rotational aerodynamic characteristics of the X-31 were determined in earlier tests performed by Bihle Applied Research utilizing the rotary-balance rig located in the NASA Langley 20-Foot Spin Tunnel. In the normal flight regime, the basic airplane is highly damped in roll. However, as the aircraft approaches stall the level of damping is reduced, such that the aircraft becomes highly propelling in roll by 30 deg AOA and remains so through 60 deg AOA. The sideslip effects in this angle-of-attack region are very non-linear and vary significantly with rotation, especially where the aircraft is highly propelling at zero sideslip.

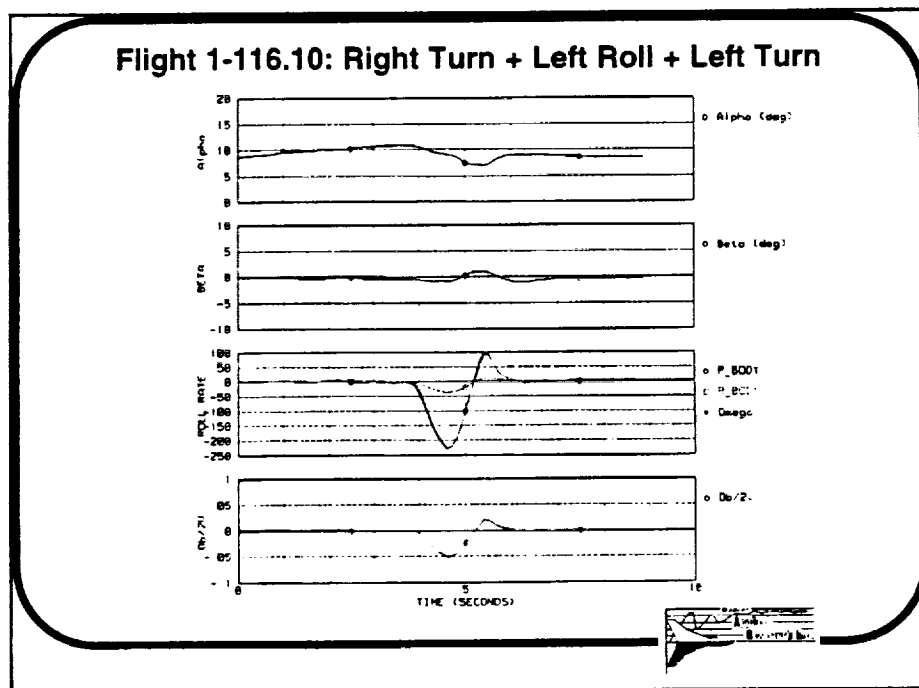


This figure displays the propagation of rolling moment versus time for the flight test data of Flt 2-85 as well as the original simulation, which did not incorporate the rotational data. As shown, the original model exhibited a poor match with flight.

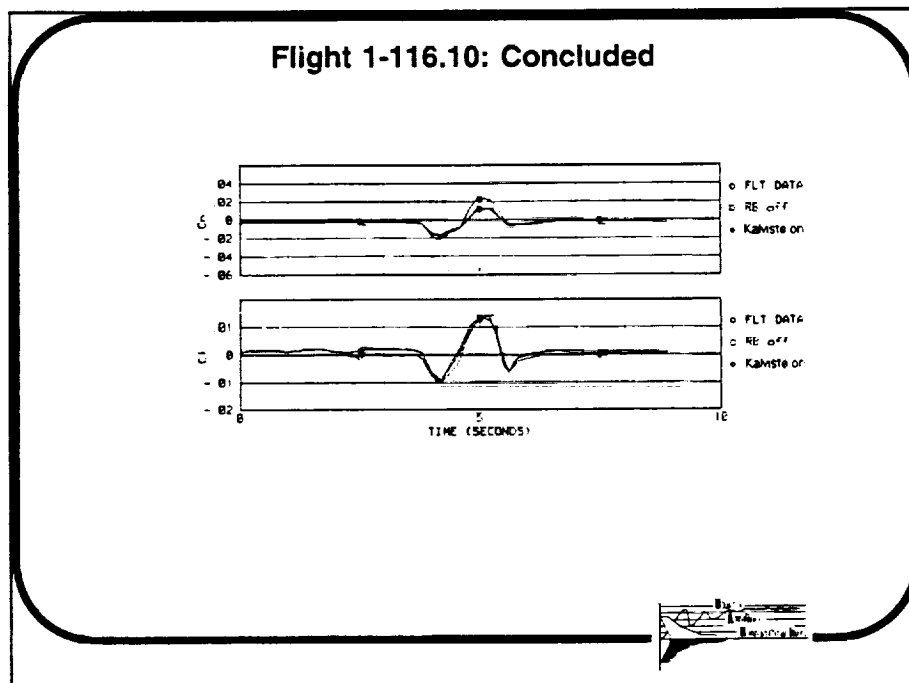
Because the model, as originally mechanized, would roll in the opposite direction when driven with the flight test control inputs, the test center attempted to improve the match by significantly reducing the lateral stability. Even with these changes, the match was less than satisfactory. The total dynamic roll contribution from the combination of the roll and yaw rate damping terms is shown for the coordinated roll using the conventional buildup, and is seen to be significantly less propelling than the rotational damping increment that results if the Kalviste technique is used instead. When this increment is utilized as the dynamic contribution in rolling moment due to the velocity vector roll, as shown in the final rolling moment comparison, a very good match with flight test data is obtained.



Flight 1-116.10, a 10 deg AOA right turn followed by a roll to the left and left turn, was investigated to check the model mechanization technique at low angles of attack. This first figure presents the angle of attack, angle of sideslip, and the rate traces for the maneuver. Because of the low angle of attack and the coordination of the maneuver, the body-axis roll rate is essentially equal to the wind-axis roll rate ( $\omega$ ) throughout the maneuver.



This figure presents a comparison of the total rolling and yawing moment coefficients extracted from Flt 1-116.10 with those obtained for the two cases of using only forced-oscillation data (rotary-balance terms off), and the incorporation of the rotational terms with the Kalviste technique (Kalviste on). Since these curves are identical, the damping contributions from using either the conventional or Kalviste mechanization technique must be the same.



The original NASA Dryden X-31 simulation data base exhibited significant divergence from the behavior of the aircraft seen in flight at many high angle-of-attack conditions. The fidelity of this simulation model has been significantly enhanced by incorporating several revisions to the high angle-of-attack data base and how the dynamic terms are implemented. Comparison of X-31 flight test results to the updated model response, including out-of-control motions, shows greatly improved correlation.

### **Conclusions**

- **Simulation Data Base Needs To Reflect Current Aircraft Configuration Static and Dynamic Characteristics For Proper Modeling**
- **For All High AOA Dynamic Flights Examined to Date, The Inclusion of Rotary Balance Data Using Kalviste Technique Improves Model Fidelity**
  - **Very Pronounced In Post-Stall Rolling Maneuvers as well as Departure**
  - **No Degradation at Low AOA**
- **Configuration Evaluation, Flight Control Development, Training Requirements Dictate Immediate Need For Validated Simulation Technique To Accurately Model High AOA Regime**



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